# Assessing the Effects of River Geometry and Dam Operation On Upstream Ice Conditions: Aroostook River at Fort Fairfield, Maine

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# Assessing the Effects of River Geometry and Dam Operations on Upstream Ice Conditions: Aroostook River at Fort Fairfield, Maine

by
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Hanover, New Hampshire
and
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Waltham, Massachusetts

## Assessing the Effects of River Geometry and Dam Operations on Upstream Ice Conditions: Aroostook River at Fort Fairfield, Maine

#### Introduction

Breakup ice jams frequently form in the Aroostook River downstream from Fort Fairfield, Maine and have caused severe flooding in the town. In general, the jams initially form upstream from Fort Fairfield and move downstream through town, halting in the upper reaches of the pool created by Tinker Dam (located about four miles downstream from Fort Fairfield in Aroostook Junction, Canada). The flood of record occurred on April 16, 1994 and caused damages of over \$5 million. The peak stage of 369.6 feet NGVD at Limestone Road Bridge in Fort Fairfield exceeded the previous peak stage (set in April 1993) by nearly four feet. A Federal Interagency Hazard Mitigation Team was formed following the 1994 flood to review flood history at Fort Fairfield and identify potential flood mitigation measures. As a result of recommendations made during this review, a study was undertaken to evaluate the effects of river geometry on the ice regime of the Aroostook River in the vicinity of Fort Fairfield.

The purpose of the study was to evaluate the effects of features such as shoals, islands, and bends on the conveyance of ice in the study area through the use of numerical modeling. Breakup ice jam formation and progression is a complex physical process that is highly site specific and difficult to model, and the lack of detailed historical ice records compounds the problem. This report presents the methods used to evaluate the effects of river geometry on the ice regime of the Aroostook River upstream from Tinker Dam, and whether gate operations at the dam affect this regime. We considered both freezeup and breakup conditions, and the results were verified with field measurements.

#### Authority

This study was conducted under the authority of the Corps of Engineers Section 206 Flood Plain Management Services (FPMS) Program, at the request of the Town of Fort Fairfield and the State of Maine, and was performed by the Cold Regions Research and Engineering Laboratory (CRREL) and the New England Division.

#### **Background**

The Aroostook River, located in Northern Maine, has a drainage area of about 2230 square miles at Limestone Bridge in Fort Fairfield (Green 1964). The river originates at the confluence of Millinocket and Munsungan Streams in Township 8 Range 8 WELS (West of the Easterly Line of the State). From there, the Aroostook River flows generally in a northeasterly direction to its confluence with the St. John River in Canada, about seven miles downstream from Fort Fairfield. The watershed is predominantly flat to gently sloping, heavily forested, and sparsely developed. Major tributaries include St.Croix Stream, Squa Pan Stream (the outlet of Squa Pan Lake), the Machias River, and the Little Madawaska River. Above Washburn, the average slope of the Aroostook River is 4.14 feet per mile (Green 1964). Between Washburn and Fort Fairfield, the river falls about 2.7 feet per mile. The largest drop in the river, about 80 feet, is

at the Tinker Dam Hydroelectric Project between Fort Fairfield and the confluence with the St. John River. Tinker Dam was constructed at Aroostook Falls to take advantage of the natural head for hydropower production.

As is typical in Northern Maine, breakup ice jams form annually along the Aroostook River. Jams occur between December and May, but are most common in April. Some early season jams freeze in place, while others eventually break up and move downstream. Maine Public Service Company routinely monitors ice conditions on the Aroostook River between Squa Pan and Tinker Dam. A review of recent reports indicates that breakup of the river ice cover is usually associated with precipitation. The ice covers first break up and begin to move on river reaches, but remain solid on the pools at Tinker Dam and Caribou Dam. Jams can form simultaneously at several locations, and ice jams that form upstream from Fort Fairfield move progressively downstream.

Recurring jam locations include Masardis, Ashland, Sheridan, Washburn, Crouseville, and several locations upstream and downstream from Fort Fairfield. In the vicinity of Fort Fairfield, jams have been known to form near the Caribou-Fort Fairfield town line, below Strickland Road, downstream from the Limestone Bridge, near the Fort Fairfield town garage, near the Riverside Cemetery, at the confluence with McDonald Brook, near the international border, and just upstream from Tinker Dam. The jams that cause most flooding at Fort Fairfield stop for a time at almost any point between the Limestone Bridge and Tinker Dam.

A review of existing records reveals that damaging ice jams have occurred at Fort Fairfield in at least 14 of the years between 1923 and 1994 (Acone 1994, FEMA 1994, and Kindervater 1985). Jams are recorded more frequently at the Washburn and Masardis USGS gages. Table 1 summarizes known ice events at these three locations, including stage and average daily discharge, where available. A USGS gage was located at Fort Fairfield during the period 1903 through 1910. Since that time, discharges at Fort Fairfield must be estimated using information from gages at Masardis (drainage area 892 mi<sup>2</sup>, period of record 1957 to present) and Washburn (drainage area 1654 mi<sup>2</sup>, period of record 1930 to present).

The backwater of the Tinker Dam pool, which extends into Fort Fairfield, has been considered in the past by many local residents to contribute to the formation or stopping of ice jams in the reach between the dam and the town. The original project was constructed in 1907 and consisted of a 290-ft long dam, headworks, canal, and powerhouse with two 500-KW generating units. These units were replaced in 1924 with the existing units 2 and 3 (1750 KW each). Two additional 4000 KW units were installed in 1926 and 1952, for a total installed capacity of 11,500 KW. The elevation of the main spillway crest was 342.45 ft NGVD, and the normal pool at the top of flashboards was 346.95 ft NGVD. The flashboards normally remained in place throughout the winter season and were usually taken out during the period of ice cover breakup and movement. In 1927, however, the flashboards failed during the flood of November 1927 and were not replaced before the winter season. That year, the ice jam that formed near the dam was dynamited (USACE 1950).

Table 1. Summary of known ice events at Masardis, Washburn, and Fort Fairfield, Maine

Water Year	Masardis			Washburn			Fort Fairfield		
	Date	Stage* (ft)	Average Daily Discharge (cfs)	Date	Stage (ft)	Average Daily Discharge (cfs)	Date	Stage (ft)	Average Daily Discharge** (cfs)
1923				1	<u> </u>	1	05/01/23	363.3	
1928							04/09/28	361.7	
1932							04/08/32	362.0	14,000
1934							04/15/34	363.4	
1935				04/20/35	447.1	23,300			
1936							03/18/36	363.5	18,000
1939				[			04/23/39	361.1	
1940				04/15/40	449.9	22,100	04/14/40	362.7	22,000
1941				04/17/41	446.9	11,600			
1945							03/31/45	361.6	
1946				04/30/46	446.4	19,600			
1951				04/06/51	452.2	12,300	·		
1952				04/20/52	446.9	13,900			
1953				03/30/53	450.3	17,500			
1955				12/22/54	449.8	2,260			
1956				04/18/56	444.4	5,560			
1958	12/23/57	546.44		12/21/57	451.3	550			
1959				04/11/59	447.9	7,990		1	
1965	04/20/65	539.28	2,650	12/02/64	445.4	2,480			
1968				04/13/68	446.6	11,000			
1970	04/26/70	545.22	12,500						
1971				04/24/71	447.6	6,100			
1974	12/23/73	546.68	5,000	12/24/73	457.3	14,000	12/20/73	361.7	9,500
1975				04/22/75	445.9	9,000			
1976				04/03/76	451.1	27,600	04/03/76	365.6	37,000
1978	04/23/78	543.99	4,800	04/22/78	448.3	6,620			
1980	04/12/80	542.69	2,200	04/11/80	445.1	2,600			
1981	04/06/81	544.25	8,600	04/06/81	447.6	13,600			
1982	04/24/82	546.08	8,800	04/22/82	452.1	12,000			
1984	12/16/83	545.15	2,550	04/17/84	449.9	17,000			
1985	_			04/18/85	445.3	6,000			
1986				04/02/86	448.5	12,500			
1987				04/01/87	448.8	19,200			
1988	04/04/88	543.28	5,100	04/04/88	448.4	11,400			
1989							04/08/89		
1990				04/08/90	454.2	7,800			
1991	04/12/91	545.29	12,900	04/11/91	453.9	30,000	04/11/91	364.1	
1992				04/08/92	448.8	6,600			
1993				04/11/93	448.6	12,200	04/93	365.7	16,000
1994							04/16/94	369.6	28,000

 <sup>\*</sup> all listed stages below National Weather Service flood stage of 547.0 ft NGVD for Masardis gage

<sup>#</sup> above National Weather Service flood stage of 450.0 ft NGVD for Washburn gage ## discharges estimated from recorded Washburn gage data

The dam was modified in 1965 with the addition of two 9.5-ft high by 125-ft long bascule gates on the main spillway, raising the normal pool to 352.0 ft NGVD at the top of the gates. At the same time, the embankments and spillways along the canal were raised, and a new power-house and 22 MW unit were installed. The canal spillways are at the same elevation as the top of the gates. A 17-ft wide by 8.5-ft high auxiliary gate is located next to the bascule gate on the spillway. The auxiliary gate is a hinge-type gate that must be lifted with a crane once it has been dropped, and is not operated during the winter. In 1987, a fish facility was constructed to allow for the upstream passage of Atlantic Salmon at the project.

The bascule gates at Tinker Dam are used to regulate the headpond level. During normal flow conditions, the project is operated with the bascule gates up and the headpond is cycled to generate power during the day and refill the pond at night. The average drawdown is about 4 to 5 feet in the headpond during cycling<sup>1</sup>. Flow through the turbines at rated capacity and 83 feet of head is approximately 5800 cfs. As flows increase beyond about 6000 cfs, the bascule gates are lowered with the intent of holding the pool level at 352.0 ft NGVD. According to Maine Public Service Company, the spillway capacity is approximately 22,400 cfs with the headpond at elevation 352.0 with the bascule gates fully lowered and no flow through the turbines (Figure 1). Total discharge through the project at elevation 352.0 ft NGVD is 28,200 cfs with all turbines operating and the bascule gates fully lowered. When flows exceed this level (or 22,400 cfs with no turbines running), pool elevations are controlled by the discharge capacity of the spillway.

The maximum recorded pond level occurred during the ice run of April 16, 1994, when water levels exceeded 357.7 feet, the maximum level of the gage at Tinker Dam. Using data from the Water Survey of Canada gage located downstream from Tinker Dam, Maine Public Service Co. estimated that a peak flow of about 89,000 cfs resulting from a surge of ice and water due to failure of the ice jam at Fort Fairfield occurred at 2200 hours on April 16 (turbines had been shut down about two hours previously). Figure 2 presents a hydrograph at Tinker gage, showing the flow measured at 15 minute intervals during the ice-run (the instantaneous peak flow may have occurred between readings).

#### Methods

The purpose of the present study is to determine what effects the geometry of the river, especially the islands, shoals, and bends below Fort Fairfield, have on spring breakup ice runs. One goal of the study was to develop a clearer understanding of the causes of ice jam formation in the reach between Tinker Dam and Fort Fairfield. In addition, we investigated the effects of different operating regimes at Tinker Dam on the upstream ice conditions in an attempt to identify any operating schemes or channel improvements that might mitigate adverse affects.

<sup>1</sup> Personal communication, Maine Public Service Company

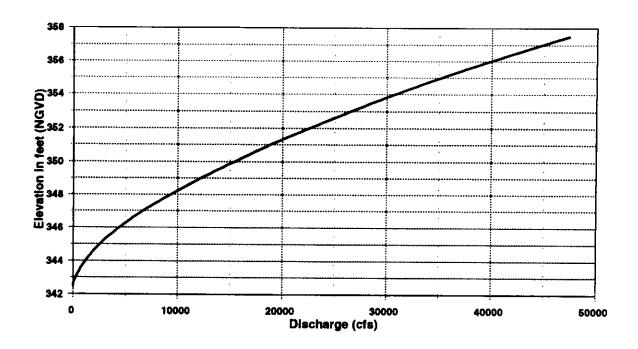


Figure 1. Discharge rating curve for the bascule gates at Tinker Dam without turbine discharge (developed from information supplied by Maine Public Service Company).

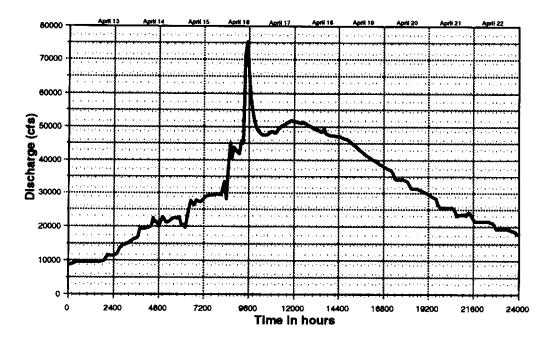


Figure 2. Hydrograph of April 1994 event at Water Survey of Canada's Tinker gage, located downstream from Tinker Dam.

The model used to perform the hydraulic analyses in this study was the HEC-2 step backwater computer program (USACE 1990), which had been used previously for open-water flood analyses (USACE 1978). This program calculates water surface profiles for steady, gradually varied flow. The effects of bridges and other obstructions to flow in the channel or flood plain can be considered in the computation. Results are based on the standard step method for determining flood profiles (solution of the one-dimensional energy equation with energy loss due to friction). Breakup ice jam formation is a dynamic, highly unsteady process. This is particularly true within the study area, where the jams form, remain in place briefly, and then shove downstream and reform. HEC-2 may not provide an accurate model of the physical processes involved in breakup ice jam formation and evolution, but it has been used successfully to calculate ice jam stages (see, for example, Wuebben et al 1992 and Gerard et al 1992).

Three cases were modeled with HEC-2 in the present study: open water, smooth ice cover at freezeup flow, and equilibrium breakup ice jams at a range of possible breakup flows, channel configurations, and operating conditions. Prior to the start of modeling, a review of existing river geometry information used in the Flood Plain Information (FPI) Study (USACE 1978) indicated the need for additional information in the jam area. Nine additional cross-sections were surveyed during the week of 25-29 October 1994. Three sections located in New Brunswick, Canada, were surveyed by G.H. Surveys and Consulting Engineers of New Brunswick under contract with Maine Public Service Company. The remaining six sections, located between the border and Limestone Road Bridge, were surveyed by the Corps of Engineers survey crew. Cross-section locations are shown in Figure 3.

A bottom profile of the centerline of the Aroostook River in the study reach was also obtained using a boat and a depth finder. Readings were taken about every 400 feet over the length of the study reach. Irregularities in the river invert compared to the surveyed cross-sections were noted at several locations along the river reach: at Riverside Cemetery, near the gravel pits, and in the headpond of Tinker Dam. At the cemetery and the gravel pits, a combination of the newly surveyed cross-sections and sections from the 1978 FPI were used to describe river geometry. Below-water cross-sectional information from the 1978 FPI was adjusted to reflect actual river inverts measured during the profiling. In some cases the cross sections were adjusted to be lower, in others they were adjusted to be higher.

Freezeup hydraulic analysis. The open water analysis was performed to gain a better understanding of ice cover formation processes within the study reach during freezeup. Using HEC-2, we computed water surface profiles for discharges of 500, 1000, 1500, 2000, 2500, and 3000 cfs. In addition, hydraulic characteristics for the river, such as Froude number, were analyzed to further support anecdotal accounts of thermal ice growth on the river. A typical early winter freezeup flow at Fort Fairfield is 2,000 cfs. The starting water surface elevation was the normal pool elevation, 352.0 ft NGVD. We also compared results for a starting water surface assuming the gate fully lowered. As discussed later in the report, it appears that operating Tinker Dam with the gate up during freeze up results in a smooth, thermally grown initial ice cover. The benefits of establishing a solid ice cover in this manner is that ice growth is then primarily controlled by thermal processes which generally results in a thinner initial ice cover than frazil ice

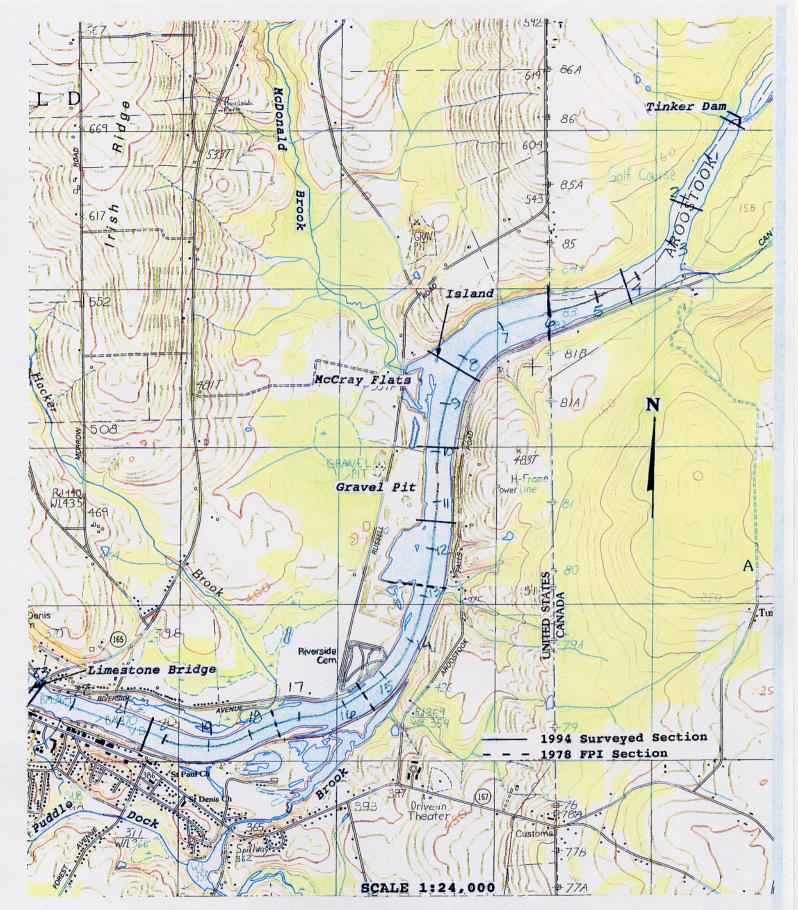


Figure 3. Map of study area showing cross-section locations.

growth, which occurs in open river reaches. After completing the open water analysis, we used HEC-2 to model a smooth ice cover, 2 feet thick. The starting water surface elevation was normal pool and the discharges were 2000 cfs and 5000 cfs, a discharge associated with higher, midwinter flows. The Manning's "n" of the smooth ice was assumed to be 0.02.

Equilibrium ice jam analysis. The ICETHK utility program (Wuebben and Gagnon in prep) was used in conjunction with HEC-2 to calculate the equilibrium ice jam thickness at every cross-section. ICETHK automates the process of first calculating hydraulic conditions with an ice cover using HEC-2, computing new ice conditions with ICETHK, and then re-calculating hydraulic conditions with the new ice conditions. The user specifies input parameters (Table 2) and the number of iterations desired. ICETHK iterates until the change in ice thickness between iterations is small, or the specified number of iterations has been attained.

An ice cover may form thermally, through the rapid growth of ice crystals on the surface of the water under quiescent conditions, or by juxtaposition or shoving. In juxtaposition, ice pieces or pans are pushed together edge-to-edge and freeze in place, normally with relatively low flow velocities. In shoving, the forces acting on the ice pieces are sufficient to cause the accumulated ice to collapse or "shove" until the ice cover thickens enough to transfer the force to the river banks and withstand the upstream forces. An ice cover formed by juxtaposition is essentially a single layer, while shoving may result in a total ice thickness many times the thickness of the ice pieces making up the ice cover.

Table 2. ICETHK input parameters.

Parameter	Value
Jam type	Breakup
Width smoothing option	No
Slope smoothing option	Yes
Initial ice thickness	2 feet
Initial ice roughness (Manning's "n")	0.020
Ice roughness	ICETHK computes (Nezhikhovskiy)
Coefficient related to the internal friction of the	1.2
ice accumulation	
Ice accumulation porosity	0.5
Cohesion factor for ice	0 (breakup jam)
Specific gravity of ice	0.916
Maximum non-eroding velocity	5 ft/sec
Maximum ice thickness increase allowed in a single iteration	3 feet
Overbank ice	Calculated by ICETHK
Water depth above floodplain at which ice goes overbank	2 times the ice thickness
Ice smoothing option	Yes
Ice smoothing threshold	2 feet

ICETHK calculates ice jam thickness for a given discharge by juxtaposition and shoving at each cross-section, and then checks that the calculated ice thickness is stable (i.e., the resisting forces of the calculated ice cover balance the forces acting in the downstream direction). If the ice thickness calculated by only one method is stable, that ice thickness is used as the equilibrium ice thickness. If the ice thickness calculated by both methods are stable, ICETHK uses the thicker of the two as the equilibrium ice thickness. The program also addresses ice in the overbanks as a result of stage rises, allowing the user to determine at what stage ice is carried into the overbanks. Ice roughness values can be provided to the program, or it will calculate them using relationships developed by Wuebben from data by Nezhikhovskiy (1964).

The ice supply at Fort Fairfield is essentially unlimited, so the model was allowed to form an equilibrium ice jam without limiting the volume of ice available to jam. Maine Public Service Company annually measures ice thickness in the Tinker Dam pool between about mid-February and mid-March and supplied data for the years 1968 through 1994, with the exception of 1981, when unsafe conditions prohibited measurements. The data, shown in Figure 4, shows a wide annual variation in ice thickness, with an overall average ice thickness of 23 inches. For the purposes of the breakup jam analysis, we assumed a parent ice thickness of two feet.

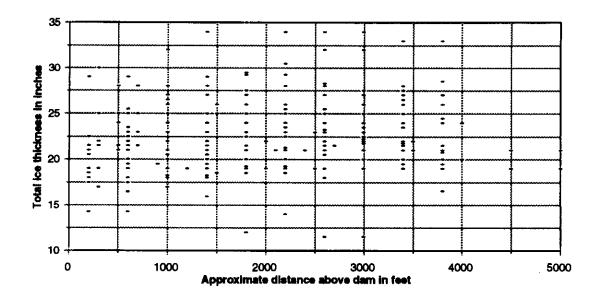


Figure 4. Measured ice thickness in Tinker Dam pool, 1968-1994 (from data supplied by Maine Public Service Company).

Note: distances upstream from the dam are approximate.

Equilibrium ice jams were modeled for several river geometries and dam gate operation scenarios (Table 3). For each case, the model iterated until the calculated ice thickness converged

on a stable result, which was then adopted as the equilibrium jam configuration for that particular scenario. We modeled the different operating scenarios by varying the starting water surface elevation at Tinker Dam using the dam rating curve (Figure 1). The existing operating scenario is referred to as the "gate-up" scenario. For the alternative operating scheme modeled, referred to as the "gate-down" scenario, the gate was assumed to have been totally lowered prior to ice cover breakup.

Table 3. Summary of breakup ice jam hydraulic analyses.

Discharge (cfs)	Initial Gate Position	Starting Water Surface Elevation (ft NGVD)	Channel Improvement
10,000	gate down	348.3	none
10,000	gate up	352.0	none
15,000	gate down	349.9	none
15,000	gate up	352.0	none
15,000	gate down	349.9	trapezoidal channel
15,000	gate up	352.0	trapezoidal channel
15,000	gate down	349.9	trapezoidal channel, dredge island only
15,000	gate up	352.0	trapezoidal channel, dredge island only
15,000	gate down	349.9	trapezoidal channel, bottom width 800 ft
15,000	gate up	352.0	trapezoidal channel, bottom width 800 ft
20,000	gate down	351.4	none
20,000	gate up	352.0	none
20,000	gate down	351.4	trapezoidal channel
20,000	gate up	352.0	trapezoidal channel
20,000	gate down	351.4	trapezoidal channel, dredge island only
20,000	gate up	352.0	trapezoidal channel, dredge island only
20,000	gate down	351.4	trapezoidal channel, bottom width 800 ft
20,000	gate up	352,0	trapezoidal channel, bottom width 800 ft
30,000	gate down	353.8	none
30,000	gate down	353.8	trapezoidal channel
30,000	gate down	353.8	trapezoidal channel, dredge island only
30,000	gate down	353.8	trapezoidal channel, bottom width 800 ft
35,000	gate down	355.0	none

Discharges of 10,000, 15,000, and 20,000, were modeled for both operating scenarios. Higher discharges of 30,000 and 35,000 cfs were analyzed using the Tinker Dam rating curve alone, since at flows over about 23,000 cfs, the bascule gates are fully lowered. Based on the open-water discharge frequency curve developed by Acone (1994), a flow of 23,000 cfs has about an 80 percent chance of being equaled or exceeded in a given year. However, ice cover breakup and jams occur at lower discharges which would have a higher exceedance probability: flow was less than 23,000 cfs during the jam formation period for six of nine relatively well-documented ice events (Acone 1994).

We evaluated the effects of three channel improvement schemes on the ice regime in the river for three discharges: 15,000 cfs, 20,000 cfs, and 30,000 cfs. The dredging we modeled was

intended to create a smooth bottom slope for the river, as shown in Figure 5. Cross-sections were assumed to be dredged to a trapezoidal shape with side slopes of 1.5V:1H. The first channel improvement assumed that the river bed was dredged in a trapezoidal shape to create a uniform bed slope from Riverside Cemetery (station 16100) to just upstream from Tinker Dam (station 2200) with the bottom width of the dredged channel set equal to the current channel width. The second channel improvement assumed that the channel was dredged from station 8900 to 8100 (the area around the islands at the confluence with McDonald Brook) and was performed primarily to remove the islands. The third channel improvement option is to dredge from Riverside Cemetery to just above the dam with the same bottom slope as the first scheme, but with a uniform channel bottom width of 800 feet for all sections in the reach. Generally, we observed only a minimal decrease in computed river stage at Limestone Bridge (less than 0.3 feet). However, a significant reduction in ice thickness just north of the gravel pits was computed by the model. This could result in ice jams releasing and moving downstream at lower upstream water stages, causing less flooding as a result. This is discussed in detail later in this report.

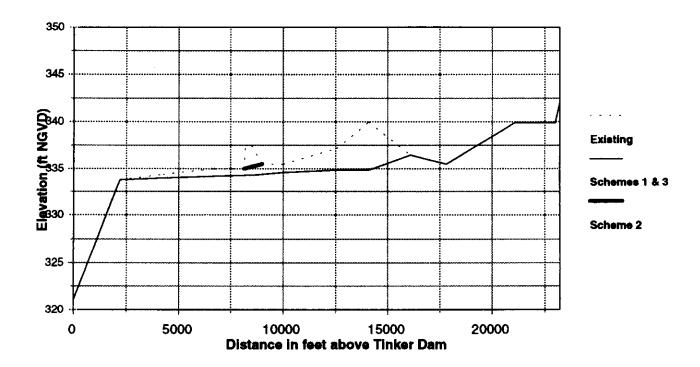


Figure 5. Graph of minimum channel elevation for existing conditions and dredging schemes 1,2, and 3 used in equilibrium ice jam hydraulic analysis.

In scheme 1, the channel bed is dredged to a trapezoidal shape, retaining the natural bottom width. In scheme 2, only the islands at McDonald Brook are assumed to be dredged. In scheme 3, the dredged channel bottom width is 800 ft. Normal pool elevation is 352.0 feet; station 0 is

Tinker Dam, and station 23200 is Limestone Bridge.

Field Measurements. Anecdotal reports of ice jam formation and movement in the Fort Fairfield area suggest that broken ice or ice jams moving downstream from above first come to a stop near the Limestone Bridge. They then move downstream, halting near the bends at Riverside Cemetery and McCray's Flats before the ice run finally clears the Tinker Dam headpond. The downstream progression of the jams is a function of many parameters, including changes in energy slope and varying degrees of downstream ice sheet thickness and competence. Some knowledge of ice cover formation and thickness is necessary in order to estimate what role the ice sheet in the study reach plays in the formation of jams.

Local sources indicate that the river freezes up rapidly, forming a smooth ice cover early in the season. Although no detailed observations of the freezeup process exist prior to the winter of 1994-1995, anecdotal evidence suggests that neither juxtaposition nor shoving play a role in the freezeup and initial formation of the ice cover in the vicinity of Fort Fairfield. In an effort to better understand the ice formation process within the study reach, Maine Public Service Company representatives made observations of ice cover formation as well as intermittent ice thickness measurements during the winter of 1994-1995. We also made ice thickness measurements in the reach between the border and Fort Fairfield on February 22, 1995.

#### Results and Discussion

Freezeup hydraulic analysis. The purpose of the open-water analysis was to investigate hydraulic conditions at freezeup. In terms of ice cover formation, the most significant parameter computed by HEC-2 is the average channel Froude number at each cross-section. The Froude number is a dimensionless ratio of inertial to gravity forces that relates flow velocity and depth. A Froude number less than 1.0 indicates that flow is subcritical; gravity forces dominate, velocities are low, and flow can be described as tranquil. Froude numbers greater than 1.0 indicate that flow is supercritical; inertial forces dominate, velocities are high, and flow can be described as rapid.

For very low Froude numbers, we would expect ice cover formation to be dominated by heat transfer processes, such as occurs on lakes. Juxtaposition of floes into a single layer can occur at channel Froude numbers up to about 0.08. At greater Froude numbers, a thicker initial ice cover resulting from shoving would be expected. Once the ice cover is formed, ice growth will be a function of heat transfer to the atmosphere or under-ice deposition of frazil or broken sheet ice. The heat transfer process is heavily influenced by snowfall on the ice and refreezing of saturated snow into ice. Locations in which shoving, snow ice formation, or under-ice deposition result in greater than normal ice thickness can provide greater resistance to the breakup and movement of ice later in the season.

The open-water analysis showed that, under current operating conditions (bascule gate up at Tinker Dam), the Froude number within the reach downstream from the Limestone Bridge is quite low and always much less than 0.08; that is, we would expect thermal processes to govern the initial ice cover formation, rather than juxtaposition or shoving (Figure 6). This is a favorable condition because the resulting smooth ice cover is relatively uniform, unlike the cover resulting from shoving where ice thickness can be highly variable and much thicker than the initial ice

cover. If the gate were lowered during freezeup, however, the open-water analysis showed an increase in water slope and velocity that resulted in Froude numbers greater than 0.08 at several locations (Figure 6). The locations where high Froude numbers indicate that shoving might occur include the Limestone Bridge, the bend near the cemetery, and above the confluence with McDonald Brook, all problem areas at the present time. If shoving were to occur in these areas at freezeup, resulting ice thickness could be greater. This would provide more resistance to downstream ice movement at break up, which could result in increased upstream flooding. We did not test the channel improvements in the open-water analysis, since the net effect of these improvements would be to steepen the slope, resulting in a thicker initial ice cover. Since existing operating conditions result in the thinnest initial ice cover by eliminating the chance of shoving and thickening, current Tinker Dam operations at freezeup appear to be best for reducing ice jam potential during spring break up.

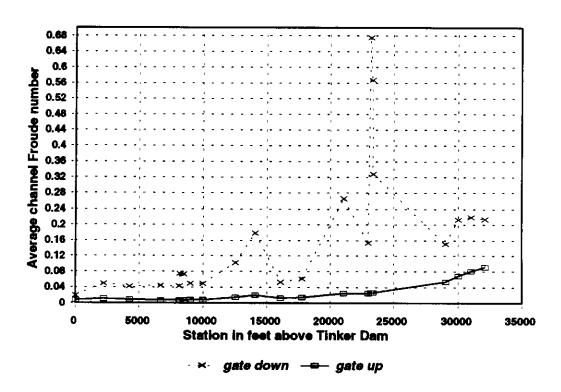


Figure 6. Average channel Froude numbers calculated in the study reach (open water, typical winter freezeup discharge of 2000 cfs).

Although the percentage of snow ice and thermally grown ice can be highly variable in a given year (Figure 7), the average total ice thickness on the Tinker Dam pool at the time of the annual measurements was fairly constant ( $22.6\pm4.1$  inches). The historical records for the reach from the dam to the US-Canadian border reveal a fairly uniform ice thickness in the reach, with some snow ice, but with no frazil deposits beneath the ice. The ice thickness measurements made between the border and Fort Fairfield on February 22, 1995 confirmed both past observations and

the open-water analysis results which indicated that initial ice formation in this reach is primarily a function of thermal processes rather than juxtaposition or shoving. The measurements, plotted in Figure 8, showed that the solid ice was quite uniform, clear in color below the frozen snow ice, and averaged 1.3 feet in thickness.

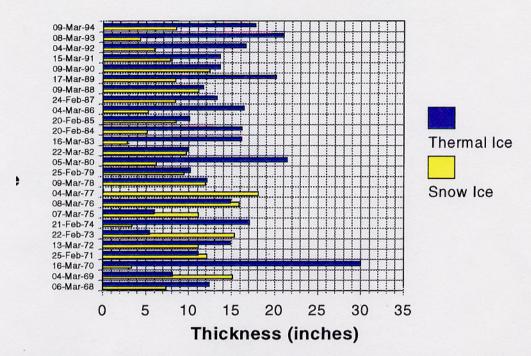


Figure 7. Historical average values of thermally grown ice and snow ice, Tinker Dam headpond (from data supplied by Maine Public Service Company).

Conversations with hydrologists at Environment Canada indicated that frazil ice can be produced throughout the winter season on the Aroostook River. In contrast to historical measurements made farther downstream in the pool, which showed no frazil deposits, we did find frazil ice at the upper end of the pool near downtown Fort Fairfield (Figure 8). At station 14250 (14250 feet upstream from the dam), there was a discernible frazil ice deposit below the ice cover that was not measurable. There was 0.75 feet of frazil deposited beneath the solid ice at station 16000, and 2.9 feet of quite dense frazil deposited at station 17000 (upstream end of Riverside Cemetery). There was no frazil deposit present at station 22500.

The presence of a frazil ice deposit near the Riverside Cemetery is significant because this is one of the known locations where ice jams pause. An ice cover thickened by such deposits could provide additional resisting forces to the downstream movement of broken ice or jams, and could be a major cause of the jam stoppage at this location. In the past, locations of frazil ice deposition have been identified using a critical deposition velocity. Frazil deposits grow from upstream to downstream in the following manner: at the most upstream location where the average cross-sectional flow velocity is less than the critical deposition velocity, frazil ice will

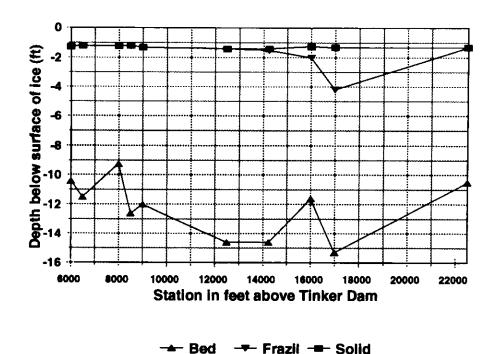


Figure 8. Ice thickness measurements made February 22, 1995. Snow ice and thermally grown ice are combined as solid ice, and zero is the top of the solid ice.

begin to deposit. Frazil will continue to deposit at that location until the critical velocity has been reached due to the reduction in cross-sectional area, and any additional frazil will be transported downstream, where the process continues. Michel and Drouin (1981) found critical velocities of between 1.64 and 3 ft/s for two reaches of the LaGrande River in Quebec. The critical velocity was observed to vary throughout the winter and with changes in river cross-section.

If the critical velocity criteria were to be applied to the Aroostook River at Fort Fairfield, we would expect to see frazil deposits at every cross-section in the study reach for discharges of about 2000 cfs. At 5000 cfs, deposits would start near the upstream end of the bridge. Clearly, the critical velocity criteria does not adequately describe the frazil deposition process at Fort Fairfield. Recently, however, Shen and Wang (1995) have proposed a new criteria for frazil deposition based on the concepts of bed load transport. When we applied the new criteria to hydraulic parameters computed by HEC-2 for 2000 cfs, we found that deposition would be predicted downstream from cross-section 17800, while frazil ice would remain in transport above that point. Our field data fits this deposition criteria quite well, with the thickest deposit at station 17000, and no deposit at station 22500. At a discharge of 5000 cfs, frazil ice would theoretically remain in transport until station 8510 (near the confluence with McDonald Brook).

This analysis indicates that frazil deposition will probably occur within the Tinker Dam head pool somewhere between stations 8510 and 17800 under normal winter conditions. At lower flows, the frazil will tend to deposit closer to the upstream end of this reach, while at higher flows, it will not begin to deposit until the lower end of this reach. The presence of the frazil

deposits appears to be quite closely correlated to the location of ice stoppages that result in ice jam flooding at Fort Fairfield. Frazil ice is produced in the open river reach below Caribou Dam. There is very little that can be done to prevent its formation, since this reach remains open all winter due to the increased turbulence associated with releases from a hydro-dam. Although the deposits we detected were found near the cemetery, during winters with higher flows, the deposits may occur further downstream near McCray's flats. The location of frazil deposits may provide some further insight into predicting where ice floes will stop in a given year, however, there is little that can be done to prevent this frazil accumulation.

If a regular program of ice thickness measurements throughout this reach was initiated by the town, this information could be combined with data already gathered by Maine Public Service Company for the Tinker Dam headpond. NED and CRREL personnel can provide technical assistance to the town to develop the best methods for collecting this data. Due to the safety concerns associated with measuring ice thickness on a river, only trained personnel should collect this data. The ice thickness should be measured each winter to further define the role that frazil deposition plays in the hydraulics of ice jams throughout this reach. This information could be used to develop potential future ice mitigation and/or prediction methods for this area. By locating frazil deposits during the winter, for example, the town may be better able to direct local ice breaking efforts in the future.

Equilibrium ice jam analysis. A one-dimensional, steady state model such as HEC-2 will not precisely model an ice jam event which consists of the downstream movement of an ice jam as a result of several successive shoving events, the pattern seen at Fort Fairfield. On the other hand, modeling an equilibrium ice jam under staeady-state conditions within the study reach using HEC-2 can provide us with information that may be used to analyze the situation. From Figure 9, we can see that the computed equilibrium ice jam results, assuming the jam toe is located at station 8500 (near the islands at McCray's Flats), generally agree with observed stages for several ice jam events at Limestone Bridge, with the exception of the April 1976 ice jam event. According to Acone (1994), most ice jams that affect Fort Fairfield have failed before 25,000 cfs, and two-thirds fail at discharges less than 20,000 cfs. Therefore, we have some confidence that the model is acceptable for discharges in the range of interest, less than about 30,000 cfs (the most typical range of flows in the study area).

Assuming that the ICETHK-HEC-2 model provides a good estimate of flood stages in Fort Fairfield for an ice jam occurring at a known location, we can then begin to examine the configuration of the equilibrium jam. Both computed water surface elevation at Limestone Bridge and ice thickness at McCray's Flats were compared for each of the operating scenarios and dredging schemes. Since the modeling capabilities are presently limited to steady-state models and ice jams are highly dynamic phenomena, computed ice thickness was believed to be a more reliable index of improved conditions than computed stages.

Equilibrium ice thickness can be considered an indication of the relative propensity of a jam to thicken at a certain location. We assumed that thicker ice accumulations would withstand larger forces from upstream and stay in place longer than thinner ice accumulations. The severity

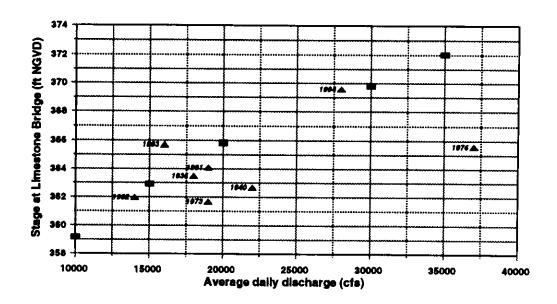


Figure 9. Comparison of observed stage at Limestone Bridge during selected ice events (△) and estimated stage resulting from an equilibrium ice jam with a downstream toe located at station 8500 and a parent ice thickness of 2 feet (□).

of ice jam flooding in Fort Fairfield appears to be related to the amount of time that the jam remains in place, allowing river stages to increase. As a result, we believe that a reduction in computed ice thickness, which may result in the jam releasing downstream at lower discharges and lower upstream river stages, is a more significant indication of improved conditions than the computed reduction in stage with the jam in place. Using ICETHK, stages are calculated for a given discharge with the equilibrium ice jam in place at one location, while the jams at Fort Fairfield are generally the result of several shoving events in which the ice stops for a period of time at several locations before moving further downstream and thickening. Steady-state models are not appropriate for modeling this dynamic situation.

The mean equilibrium ice thickness for the modeling conditions given in Table 3 are shown in Figure 10. Although there are many different scenarios included in this computed mean ice thickness, in all cases, the thickest deposits of ice occurred in the immediate vicinity of station 10000. Initial thickening begins to occur about 8500 feet upstream from Tinker Dam, near the confluence with McDonald Brook. The location of the initial thickening coincides with the island-delta formation at the mouth of the brook, a known jam stopping point. The largest amount of thickening occurs about 10000 feet upstream from the dam in the area known as McCray's Flats near the downstream end of the gravel pits on the left bank of the river. Computed equilibrium thickness at McCray's Flats ranged from just over 3 feet thick to almost 16 feet thick for the different modeling conditions. Since ice accumulations in this area were always the thickest in the model reach, we chose to compare the various schemes on the basis of the computed equilibrium ice jam thickness here, reasoning that thinner ice would be less resistant to upstream forces and would fail sooner than thicker ice, potentially reducing flood levels in Fort Fairfield.

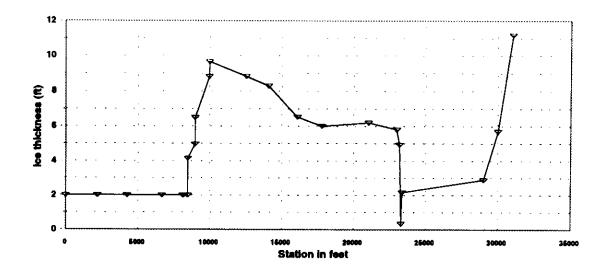


Figure 10. Plot of mean equilibrium ice thickness calculated in the study reach. Note that the zero ice thickness shown at the Limestone Bridge location is an artifact of ICETHK, which must assume zero ice thickness at bridges, and is not an estimation of the equilibrium ice thickness at this location.

Although thinning the ice near McCray's Flats is expected to result in an earlier downstream release of the ice jam, the intact ice cover on Tinker headpond will not be significantly affected by any channel improvements. The released jam is not expected to move much further downstream than about station 5000 (the vicinity of Dee's Camp). This movement downstream is expected to add significant river channel and floodplain storage for water and ice and may result in lower flood stages in Fort Fairfield. Downstream impacts of the final release of the Tinker ice cover may also be lessened due to the decreased volume of ice from the upstream river reach as a result of the thinner accumulations, however, detailed analyses of these downstream conditions were not performed as a result of this study.

Figure 11 presents the mean equilibrium ice jam thickness averaged between stations 9990 and 10000 (the index location) for each of the alternatives given in Table 3. From this figure, we can see that the thickest ice jams occur at discharges of 15,000 to 20,000 cfs with the existing river channel geometry when the Tinker Dam gates are lowered prior to jamming. The situation is improved slightly under the current operating scenario ("gate up"). Dredging the island between about 8100 and 8900 appears to show the most promise in reducing ice jam thickness at the index location, followed by dredging the river to a uniform slope between Tinker Dam and. station 16100. However, the ice thickness at the Limestone Bridge is not affected greatly by the alternative methods, and in fact is generally thinner with the current geometric and hydraulic conditions.

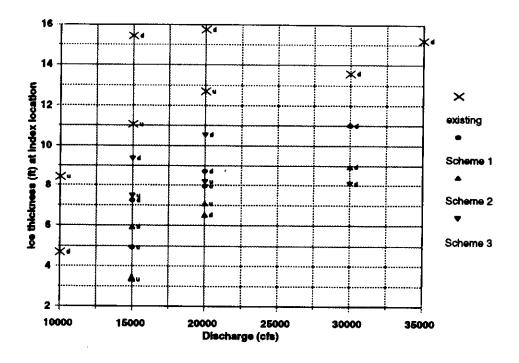


Figure 11. Results of the equilibrium ice jam hydraulic analyses in terms of average ice thickness at the index location. The "u" refers to a "gate up" starting water surface elevation, while "d" refers to a "gate down" starting water surface elevation. In scheme 1, the channel bed is dredged to a trapezoidal shape, retaining the natural bottom width. In scheme 2, only the islands at McDonald Brook are dredged. For scheme 3, the dredged channel bottom width is 800 ft.

As stated previously, computed river stages at Limestone Bridge were also analyzed for each of the operating and dredging schemes. In comparison to the significant reduction in ice thickness, there is little difference in computed water stages at the bridge for the different options. The dredging schemes generally result in lower stages at the bridge than current conditions; however, the average stage decrease was less than 0.3 feet. Based on this negligible decrease in stage, it would not appear that dredging the river would greatly improve ice jam flood conditions in the town of Fort Fairfield. However, when computed ice thickness at station 10000 is used as an index of improvement, dredging the island area appears to decrease the computed equilibrium ice jam thickness by an average of 5 feet. This decrease in ice thickness could be significant if it results in jams releasing at a lower upstream river stages, meaning less flooding in Fort Fairfield.

#### **Conclusions**

We modeled freezeup conditions at current dam operating conditions within the study reach and confirmed past observations that the river freezes rapidly into a smooth ice sheet. A thicker, rougher ice sheet would result if the bascule gates were lowered during freezeup. This is a less desirable condition due to the potential for increased resistance at breakup from the thicker ice, therefore, the gates at Tinker should be left up during initial river freezeup.

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The freezeup analysis with a smooth ice cover predicted that frazil ice deposition would occur near the Riverside Cemetery. This deposition, confirmed by field measurements, could be a significant factor in determining the location of jam stoppages in the reach of river immediately below Fort Fairfield. The Town of Fort Fairfield should initiate an ice monitoring program in the reach near Riverside Cemetery to monitor this situation. The location of frazil deposits may provide some further insight into predicting where ice floes will stop in a given year, however, there is little that can be done to prevent this frazil accumulation.

Based on our analysis of equilibrium ice jam formation with existing river geometry, the existing gate operating procedure at Tinker Dam (the "gate up" case) is preferable to lowering the gates during the breakup season prior to jamming. This may be due to the increased energy slope in the river caused by dropping the bascule gates, which results in a thicker ice accumulation at McCray's Flats. Since this is a known ice jam stopping point, any increased jam thickness in this reach is expected to further resist movement downstream, resulting in higher flood levels in the town.

The model indicates that dredging the river is an improvement over current river geometry. Scheme 2, dredging only the island-shoal area of the river (stations 8100 to 8900), seems to result in the greatest reduction in ice jam thickness. If dredging is expected to be performed for any reason in the river (i.e., removal of gravel), removal of the shoal should be investigated further. Dredging the entire river reach from the Riverside Cemetery to Tinker Dam (schemes 1 and 3) also results in a reduction in ice accumulation, however, environmental impacts and costs associated with a major dredging operation such as this makes it a less desirable option.

Scheme 2 appears to be the most feasible option for improving hydraulic characteristics of the river through dredging. This scheme involves dredging the island-shoal area to remove the sediment deposit at this reach. An area about 800 feet long by 1000 feet wide would be impacted (detailed hydrographic surveys are needed to define precise limits of dredging). We note that dredging is often only a temporary solution in movable-bed rivers. Sediment initially deposited in this reach for several reasons, including the typical delta formation process at the confluence with McDonald Brook. In addition, the Aroostook River widens here, further reducing low water velocities and encouraging sedimentation. Existing frazil deposition, which increases resistance to downstream movement of ice, is expected to continue unaffected by dredging. All of these factors will still influence the hydraulics of this area after dredging, and may offset the benefit of any dredging operations. At present, it does not appear that dredging would have any adverse impact on ice movement through this reach. At best, the ice accumulations in the area will be thinner, resulting in the jams failing at lower discharges and lower upstream river stages. At worst, conditions would be unchanged.

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